SR Motor Design with Reduced Torque Ripple

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Overview

• Motivation

• Review of SRM Theory of Operation
  – Theory of Operation
  – Mathematical Analysis
  – Definition of the SRM’s “Base Speed”
  – SRM’s Torque Ripple and Performance

• Optimization of the Conventional SRM

• New SRM Geometry
  – Torque Ripple and Performance
  – Physical Airgap and Acoustic Noise

• Outlook
Theory of Operation
SRM - Theory of Operation

• Characteristics of the SRM:
  – the SRM is a “constant power” machine
    • similar to a series wound motor
  – it is well suited to operate efficiently over a wide speed range and at very high speeds
    • does not require sinusoidal waveforms
    • requires excitation with high harmonic contents for efficient operation
SRM - Theory of Operation

• The torque output of the SRM can be controlled by regulating the current:
  – current limit
  – phase angle control (natural commutation)
SRM - Theory of Operation

- The SRM generates torque in all regions where

\[
\frac{dL(i, \Theta)}{d\Theta} \neq 0
\]

- The inductance \( L \) is a function of the current \( i \) (saturation) and the angle of rotation \( \Theta \):

\[
L = L(i, \Theta)
\]
SRM - Theory of Operation

Inductance distribution of a typical SRM

Picture courtesy Prof. T.J.E. Miller
SRM - Theory of Operation

Inductance and torque distribution of a typical SRM
SRM - Theory of Operation

• Characteristics of the SRM:
  – can operate both as a motor and a generator
  – the SR Generator is a current source
    • generation process needs energy to be excited
    • once the phase is exited it is difficult to control
Mathematical Analysis
SRM - Mathematical Analysis

• The mathematical analysis of the SR motor is challenging due to:
  – non-linear airgap
  – non-linear saturation

• Closed form models do exist for the SRM
  – linear case: \( T = f(i^2) \)
SRM - Mathematical Analysis

• Simulations are typically used to analyze the SRM:
  – FEA (finite element analysis)
  – PC-SRD (SRM Analysis software)
    • Prof. Tim Miller, Glasgow, Speed Consortium
    • Motorsoft Inc. is US distributor
  – custom software
Definition of “Base Speed”
SRM - Definition of “Base Speed”

- The SRM allows the designer great flexibility when selecting a suitable motor winding

- To better compare machines we need to
  - define a specific operating point
  - define a specific winding
SRM - Definition of “Base Speed”

• When a single winding of the SRM is energized we can determine the winding current as:

\[ V = R \cdot i + L(i, \Theta) \cdot \frac{di}{dt} + \omega \cdot \frac{d\Phi}{d\Theta} \]

where

- \( V \) is the applied bus voltage
SRM - Definition of “Base Speed”

• We now define the base as the speed, where

\[
 L(i, \Theta) \cdot \frac{di}{dt} + \omega \cdot \frac{d\Phi}{d\Theta} = 0
\]

thus the current \( i \) is constant throughout the region of the inductance change
SRM - Definition of “Base Speed”

- Motor operating at base speed

efficiency 89.6%
SRM - Definition of “Base Speed”

- Motor operating above/below base speed

efficiency 90.4% (above)  
efficiency 87.6% (below)
SRM - Definition of “Base Speed”

• The “base speed” is a point of comparison
  – it is a good point of reference
  – it is an efficient operating point
  – allows better comparisons between different motor designs
  – simulations do show that the efficiency of the SRM drops at speeds greater than 2x”base speed”
Torque Ripple and Performance
SRM - Torque Ripple and Performance

- Design of a typical SRM

6/4 design
3 phase
matched pole geometry
SRM - Torque Ripple and Performance

- Design of a typical SRM

- Shaft power: 1.0 kW
- Efficiency: 85.1%
- Min/ave torque: 32%
SRM - Torque Ripple and Performance

- Improved Commutation of a typical SRM

shaft power: 1.0 kW
efficiency: 82.7 %
min/ave torque: 71 %
SRM - Torque Ripple and Performance

- Torque ripple appears to be reduced as the rotor tooth is widened

<table>
<thead>
<tr>
<th>Power</th>
<th>3.1 kW</th>
<th>2.5 kW</th>
<th>1.8 kW</th>
<th>1.3 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>eff.</td>
<td>89.6%</td>
<td>89.6%</td>
<td>90.2%</td>
<td>89.3%</td>
</tr>
<tr>
<td>min/max</td>
<td>39%</td>
<td>48%</td>
<td>54%</td>
<td>67%</td>
</tr>
</tbody>
</table>
SRM - Torque Ripple and Performance

- as the rotor angle widens, the power output drops
  - some correction can be made in the winding

Power: 3.0 kW
eff.: 88.6%
min/max 92%
The $\frac{n}{n+2}$ SRM
The $\frac{n}{n+2}$ SRM

- Design of a 6/8 SRM

6/8 design
3 phase
mismatched pole geometry
The $n/n+2$ SRM

- Design of a 6/8 SRM

  shaft power: 1.0 kW
  efficiency: 86.7%
  min/ave torque: 88%
The n/n+2 SRM

• Theory of Operation of the n/n+2 design
  – the n/n+2 design results in a physically smaller airgap (tangential direction) and a more rapid saturation of the rotor tooth
  – the n/n+2 design requires mismatched poles to achieve a wide enough zero torque zone to assist the commutation
The $n/n+2$ SRM

• Advantages of the $n/n+2$ design
  – reduced torque ripple
  – improved efficiency
  – potentially lower noise
  – advantageous flux distribution 12/10
The n/n+2 SRM

- advantageous flux distribution
The n/n+2 SRM

- Disadvantages of the 6/8 design
  - requires mismatched poles
  - commutation angles become more critical
  - variable commutation angles are required for efficient operation
The $\frac{n}{n+2}$ SRM - Test Results
The $n/n+2$ SRM - Test Results

- The $n/n+2$ design offers advantages in some applications where low torque ripple is required
- The 4/6 motor is a 2 phase motor with improved starting torque
- We have built a 4/6 motor and its performance matches the simulations
- The motor has been tested up to 24 kRPM
The \( n/n+2 \) SRM - Test Results

- No comparative measurements of the acoustic noise between a 4/2 and a 4/6 motor have been performed to date.

- Worldwide patent applications have been filed to protect the \( n/n+2 \) SRM geometry.
The $n/n+2$ SRM - Future Work
The n/n+2 SRM - Future Work

• A more detailed analysis of the motor’s acoustic noise will be performed

• Several other n/n+2 motors are under construction to further validate the concept
The n/n+2 SRM - Future Work

- Potential Applications:
  - Automotive fuel and water pumps (2 phase)
  - Refrigeration compressors (2 phase)
  - Small appliances (3 phase)